Topology and Vortex Structures of Turbine Cascade with Different Tip Clearances

HAN Wan-jin, YANG Qing-hai, HUANG Hong-yan, JIA Lin
(Academy of Energy Science and Engineering, Harbin Institute of Technology, Harbin 150001, China)

Abstract: This paper uses the topology theory to analyze the surface flow spectrums of straight, positively curved and negatively curved cascades with relative tip clearances of 0.023 and 0.036, finds apparent differences of topology and vortex structures in the blade tip and the suction side wall corner of single type of cascade with this two clearances, and studies the mechanism of the difference formation as well as their effects on the energy loss.

Key words: turbine cascade; blade tip clearance; flow visualization; topology and vortex structures

在不同叶顶间隙下涡轮叶栅的拓扑与旋涡结构. 韩万金, 杨庆海, 黄洪雁, 贾琳. 中国航空学报(英文版), 2002, 15(1): 18-26.

摘　要: 应用拓扑原理分析了叶顶相对间隙为 0.023 和 0.036 的涡轮直叶栅和正、反弯叶栅的壁面流谱, 发现在两种间隙下同类叶栅的拓扑与旋涡结构在叶顶和吸力面壁角明显不同, 探讨了差别形成的机理及其对能量损失的影响。

关键词: 涡轮叶栅; 顶部间隙; 流动显示; 拓扑与旋涡结构
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The operating tip of most gas turbines is between 1% and 5% of blade height[1] due to the mechanical structure, overheat condition, eccentricity, and other reasons. Similar case exists in the guide blade and the adjustable guide blade which, rotating around the radial axis, is installed to control the flux. Thus there may be three clearances in a turbine stage. For a long time, the radial clearance of a turbine stage has been considered as one of the causes of great decrease in turbine efficiency. The theory and experimental researches show that every 1% increment of the blade tip clearance is responsible for 1.5% reduction in turbine efficiency. This strong effect has attracted turbine designers to work hard to attain the least clearance and to reduce the loss under a given clearance. So far, many ways to reduce losses have been brought forward with many achievements. But it is still difficult to extend the methods that succeed in one turbine to the others; sometimes, inappropriate uses may even cause an acutely increasing loss. This is mainly due to the inadequate comprehension of loss creating mechanism. Ref.[3] shows that in order to understand thoroughly the mechanism of loss creating, it is necessary to measure the flow field parameter, visualize the flow spectrums of the wall surface in detail, then analyze the results of measurement and visualization solution by topology theory and require the topology and vortex structures. By the way above, the authors obtain the topology and vortex structures of a gas turbine rotor cascade with 0.023 relative blade tip clearance, and expound the mechanism that blade positive curving reduces the amount of relative leakage and leakage loss[4]. Specialists abroad pointed out that the topology and vortex structures of clearance flow are different under different relative blade tip clearances[5]. So what are the topology and vortex

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structures under different relative blade tip clearances and whether the blade positive curving is able to reduce the amount of the relative leakage and leakage loss under the condition of any relative tip clearance are the two important problems which are brought forward in engineering practice to be solved by theoretical analyses of experimental results.

1 Experimental Model

Three sets of cascades were experimented: (1) conventional straight cascade; (2) blade cascade positively curved at both ends; (3) blade cascade negatively curved at both ends (Fig. 1). The blade profiles in the parallel end wall planes are adopted from Ref. [6], but enlarged by 1.73. The other important geometric and aerodynamic parameters of blade cascade are as follows.

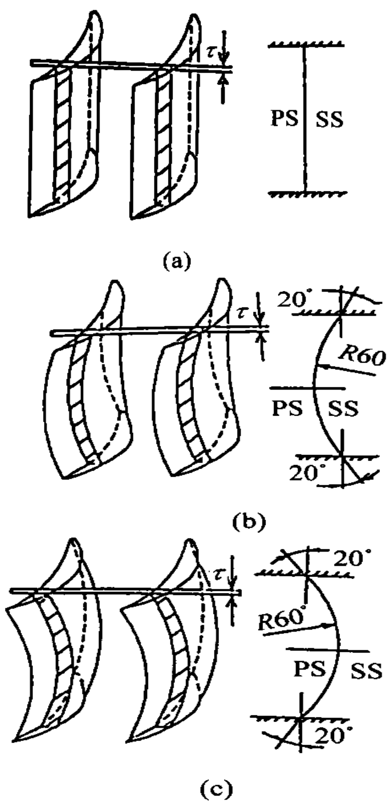


Fig. 1 Experimental model
(a) conventional straight cascade;
(b) positively curved cascade;
(c) negatively curved cascade

Blade chord $C = 121$mm; Axial chord $B = 120$mm; Pitch $s = 90$mm; Aspect ratio $h/C = 0.905$; Pitch-chord $s/C = 0.74$mm; Ratio of maximal thickness of profile to chord $M/C = 0.257$; Radius of blade leading edge $R_1 = 6.75$mm; Radius of blade trailing edge $R_2 = 3.37$mm; Cascade inlet angle (measured from the axial direction) $\alpha_1 = 50°$; Cascade exit angle $\alpha_2 = 57°$; Relative clearance of blade tip $\tau/h = 0.023$ and 0.036; Inlet total pressure $P_0^* = 10730$Pa; Mach number at the mid-span of exit plan $Ma = 0.3$; Reynolds number based on the chord $Re = 8.3 \times 10^5$; Thickness of inlet endwall boundary layer $\delta = 14$mm.

2 Topology Rule for the Blade Cascade Wall with Tip Clearance

The annular or rectangle cascade surface with a blade tip clearance can be divided into two unattached surfaces of the shell and a rotor surface. The rotor surface includes the blade surface and hub wall. A friction line surrounds this surface with many singular points.

First for the rotor surface, suppose that there is no clearance between the blade and hub, and rotor axis is a rigid body. Extending the axis towards upstream and downstream to an infinitely far distance to make the flow uniform. Either side of the axis should have a node. In topology, a three-dimensional rotor surface can be transformed into a spherical surface. Thus, the number of singular points in the rotor surface should satisfy the following equation

$$\sum N_{ab} + 2 - \sum S_{bh} = 2$$

Hence

$$\sum N_{ab} - \sum S_{bh} = 0 \qquad (1)$$

where $\sum N_{ab}$ and $\sum N_{bh}$ represent the total numbers of node and saddle points in the blade and hub surface respectively.

Second, for the shell surface, also extend it towards upstream and downstream to infinity and then transform it into an annulus by bending it and connecting its two ends. Because the friction line surrounds the annulus, there are no singular points in the region away from the enclosed cascade. Hence the number of singular points in the shell

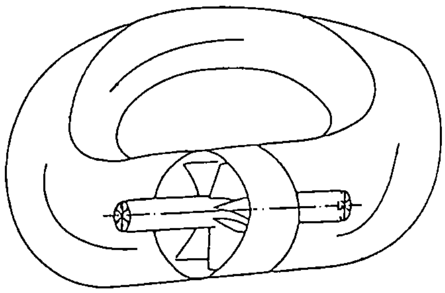


Fig. 2 Sketch of annular cascade with tip clearance

surface within one pitch should satisfy the following rules

$$\sum N_c - \sum S_c = 0 \qquad (2)$$

where $\sum N_c$ and $\sum S_c$ denote the total numbers of node and saddle points in the shell surface.

The topology rule for the wall flow field of the blade cascade with the tip clearance is acquired by adding formulas Eqs. (1) and (2)

$$\sum N - \sum S = 0 \qquad (3)$$

where $\sum N = \sum N_{bh} + \sum N_c$, $\sum S = \sum S_{bh} + \sum S_c$. So the total number of node points is equal to that of saddle points in the solid surface of the blade cascade with the tip clearance in the whole or within one pitch.

3 Experimental Results and Discussions

3.1 Topological structure of upper endwall flow field

From the flow ink trace visualization photo it can be seen that, in both relative blade tip clearances, the three sets of cascades have basically the same flow spectrums, so they have the same topology structure. The types and numbers of singular points are the same, but their positions are a little different. As is shown in Fig. 3, special flow spectrums of dual saddle points and dual nodes are formed in the leading edge of the blade tip, and there are respectively a separation line and a reattachment line near the blade tip suction surface and pressure surface extending to downstream. There are three saddle points, two attachment nodes and one separation spiral separation point, which satisfies Eq. (1) of the topology rule.

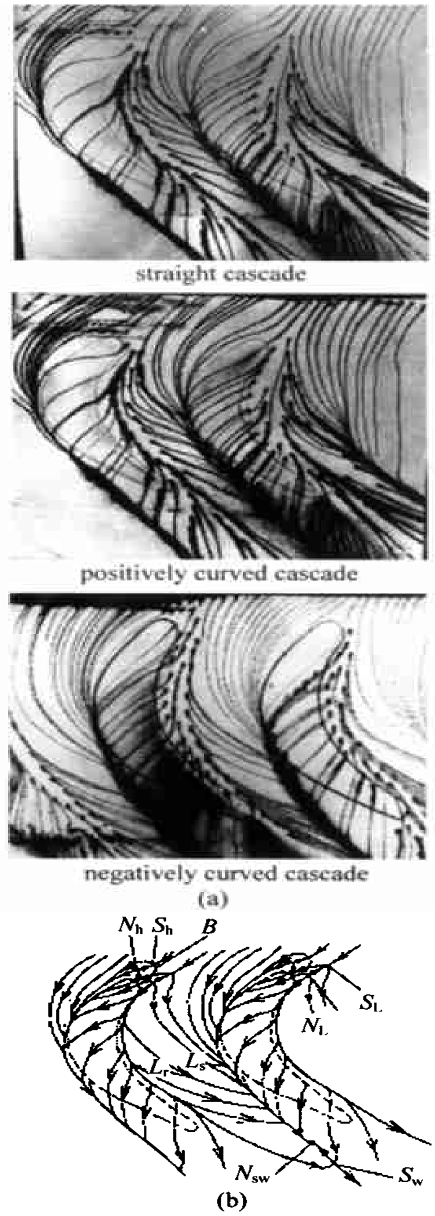


Fig. 3 Ink trace visualization photo of upper endwall flow field and its topology structure (τ = 0.023 and τ = 0.036)
(a) ink trace visualization photo of upper endwall; (b) topology structure

3.2 Topological structure of the flow field on the lower wall and blade surface

The ink trace visualization photos and their corresponding topological structures of the three sets of cascades under τ = 0.023 are respectively shown in Fig. 4 and Fig. 5. Obviously, in the suction surface of the lower half span, lower endwall and pressure surface, topological structures of the three sets of cascades are the same except for the different creating positions of the singular point

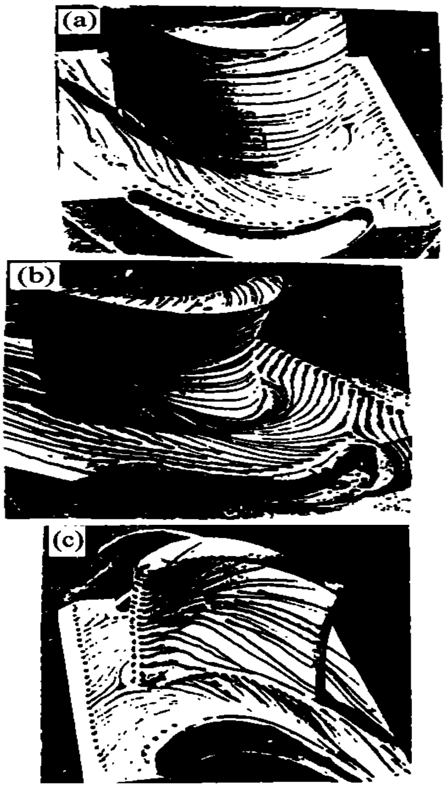


Fig. 4 Ink trace visualization photo of lower endwall and blade surface
(a) conventional straight cascade;
(b) positively curved cascade;
(c) negatively curved cascad

(Fig. 5). In the upper half span of the suction surface and the blade tip, the conventional straight cascade and negatively curved cascade have basically the same topology structures, both creating the close separation of boundary in the suction surface corner of the blade tip. Two separation lines corresponding to the blade tip suction side separation vortex and upper passage vortex extend from saddle point S_c towards downstream. Compared with the two sets of blade cascades, the topology structure of the positively curved blade is clearly different in two places. Saddle point S_c and the separation line corresponding to the upper passage vortex disappear, and the separation line corresponding to the blade tip suction side separation vortex originates from a non-singular point, so the separation vortex is formed by the open separation.

There are five saddle points, three separation nodes and two attachment nodes respectively in the flow field of the upper endwall and blade surface of the straight and negatively curved cascades, while

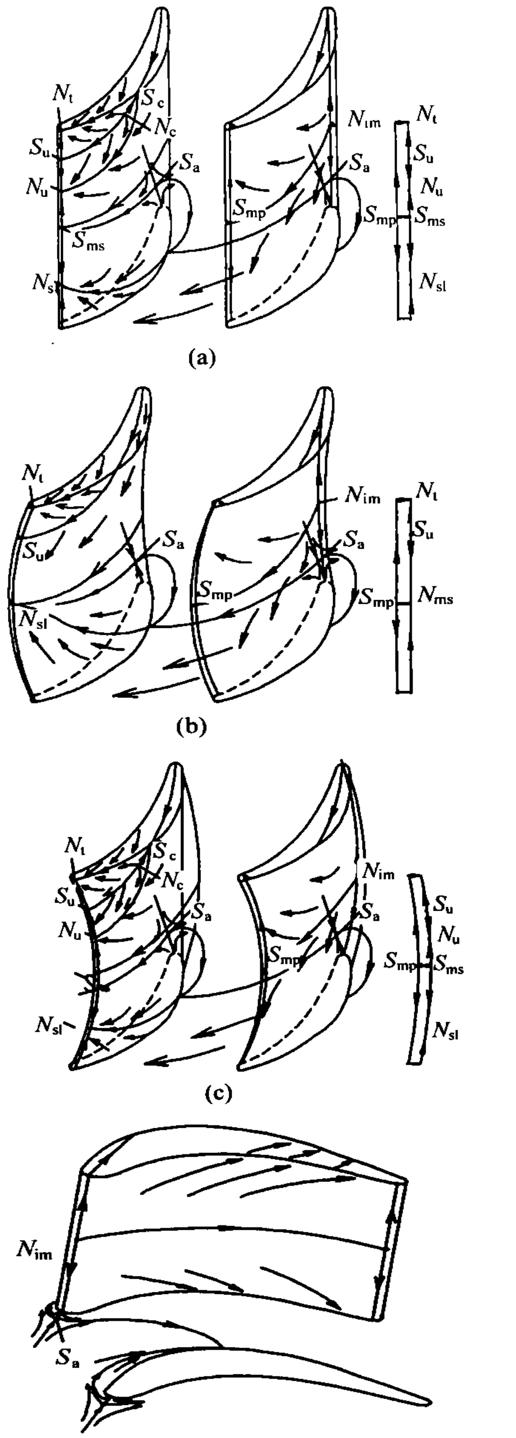


Fig. 5 Topology structures of blade surface and lower endwall
(a) conventional straight cascade;
(b) positively curved cascade;
(c) negatively curved cascade;
(d) pressure surface of the three cascades

there are three saddle points, one attachment node and two separation nodes in the positively curved cascade. The numbers of singular points in the three sets of blade cascades satisfy the topological rule shown in Eq. (2).

The topology structures of the straight, positively curved and negatively curved blade cascades are obtained by combining the flow fields of the upper endwall, blade surface and lower endwall. Obviously, there are eight saddle points, four attachment nodes, three separation nodes and one separation spiral node in the wall surface flow field of the straight and negatively curved cascades respectively. While there are six saddle points, three attachment nodes, two separation nodes and one separation spiral node in the wall surface flow field of the positively curved cascade. So the numbers of singular points of the three sets of cascades satisfy the topological rule in Eq. (3).

The ink trace visualization photos and topological structures of the three sets of cascades with $\tau = 0.036$ are respectively shown in Fig. 6 and Fig. 7. It is known, through studying how the airflow in the clearance is under forces, that the airflow microelement in the clearance is mainly affected by three forces. Of the three forces, one is the pressure gradient originating from the pressure distinction between the blade pressure side and suction side, another is the inertia force controlled by the entry velocity of the flow air, and the third is the viscosity force created by the interaction of air viscosity with the upper and lower endwalls. With the increasing of relative clearance, the pressure gradient remains the same, viscosity force wakens, and inertia force strengthens, so the wall flow spectrums under these influences will be changed.

Comparing the topology structures on the blade surface and lower endwall of conventional straight cascades with relative clearances of $\tau = 0.036$ and $\tau = 0.023$ shows that the essential difference lies in the blade tip and blade suction surface endwall. While $\tau = 0.036$, a close separation region originating from saddle point S_d is formed in the blade tip, and two separation lines correspond to the pressure side separation vortex and suction side separation vortex respectively. There is only one separation line originating from saddle point S_c in the blade tip suction surface of the blade tip,

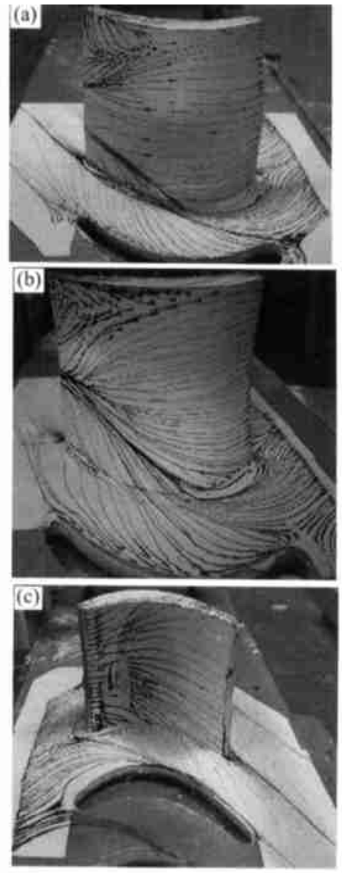


Fig. 6 Ink trace visualization photo of lower endwall and blade surface
(a) straight and negatively curved cascade;
(b) positively curved cascade;
(c) pressure surface of the three cascades

which corresponds to the separation vortex in the suction side of the blade tip. In the suction surface corner of the blade root, a close separation region originating from saddle point S_b is also formed while $\tau = 0.036$. This separation region covers the wall corner of the blade root, and is named the separation bubble, two separation lines of which correspond to the lower passage vortex and suction side wall corner vortex respectively. But under $\tau = 0.023$, here exists only one separation line, which corresponds to the lower passage vortex, and the separation is created only in the lower suction surface of the cascade. Under $\tau = 0.036$, there are in total nine saddle points, four attachment nodes, four separation nodes and one separation spiral node in the blade surface and upper endwall surface

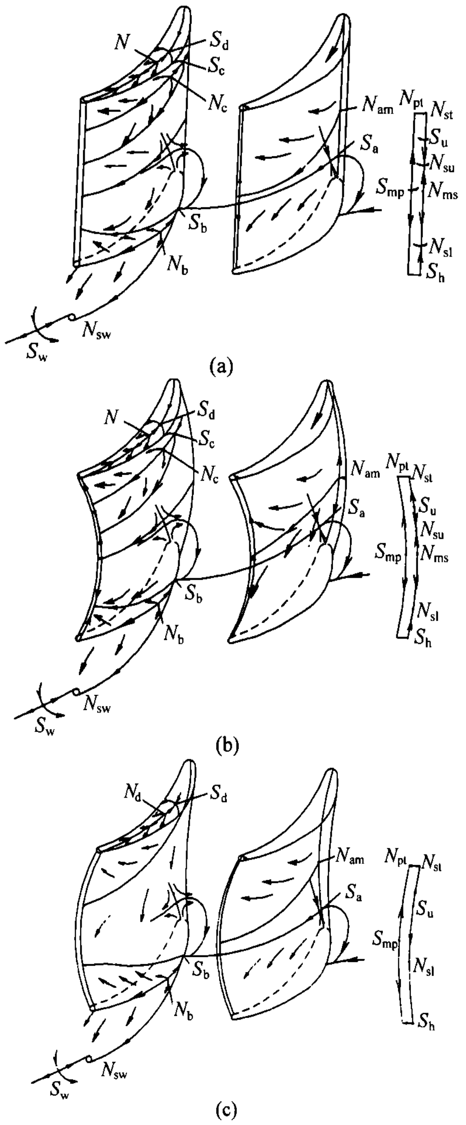


Fig. 7 Topology structures of wall surface flows of blade surface and lower endwall
(a) conventional straight cascade;
(b) negatively curved cascade;
(c) positively curved cascade

flow field of the conventional straight cascade, and the number of singular points satisfies the topological rule of Eq. (2).

By comparison of the topology structures of the three sets of cascades with $\tau = 0.036$ it can be seen that the structure of the conventional straight cascade is basically the same with that of the negatively curved cascade except a clear difference between the positively curved cascade and the other two in the upper wall corner of the blade suction side. Fig. 8 (b) shows that both the saddle point S_c and the upper passage vortex separation line disappear; only the separation line on the suction side of the blade tip and one reattachment line go through it. Because the close separation region is eliminated, the pressure on the suction side does not decrease lower. Besides, since the passage vortex is eliminated, only the leakage vortex and the blade tip suction side separation vortex participate in the interaction of vortices in the suction side corner region of the blade tip.

Under $\tau = 0.036$, there are altogether seven saddle points, three attachment nodes, three separation nodes and one separation spiral node in the blade surface and the upper endwall surface flow fields of the conventional straight cascade, and the number of singular points satisfies the topological rule of Eq. (2).

3.3 Forecast of vortex structure

Under $\tau = 0.023$, the vortex structures of the three sets of cascades are shown in Fig. 8. The vortices structures of the conventional straight

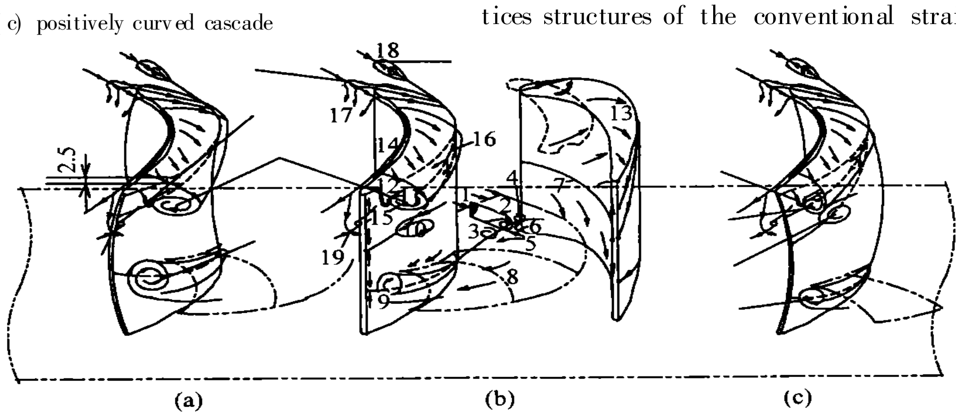
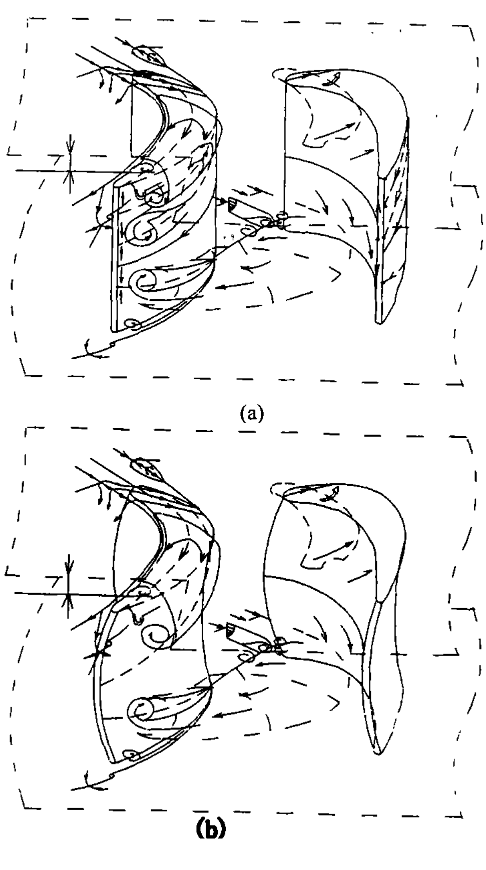


Fig. 8 Vortex structure of cascade with tip clearance ($\tau = 0.023$)
(a) positively curved cascade; (b) conventional straight cascade; (c) negatively curved cascade

cascade and negatively curved cascade are basically consistent except the differences in the vortex position, intensity and scale. Two sets of cascades both have seven separation lines on the wall surface of one pitch, which are the suction side and pressure side horseshoe vortex, upper and lower passage vortex, leakage vortex, suction side separation vortex and lower endwall inlet horseshoe vortex. In the positively curved cascade, there are only six separation lines on one pitch of the endwall, and the suction surface upper separation line disappears with its corresponding upper passage vortex, compared with the former two sets.

Under the condition of $\tau = 0.036$, the vortex structures of the three sets of cascades are shown in Fig. 9. Similarly, the vortices structure of the conventional straight cascade is consistent with that of the negatively curved cascade. The two sets of cascades both have nine separation lines on the wall surface of one pitch, which includes the upper endwall suction side and pressure side horseshoe vortex, blade tip suction side and pressure side separation vortex, leakage vortex, upper and lower passage vortex, lower endwall inlet horseshoe vortex and lower endwall suction surface corner vortex. In the positively curved cascade, there are eight separation lines, which, compared with the other two sets, eliminates the suction surface upper separation line and its corresponding upper passage vortex.



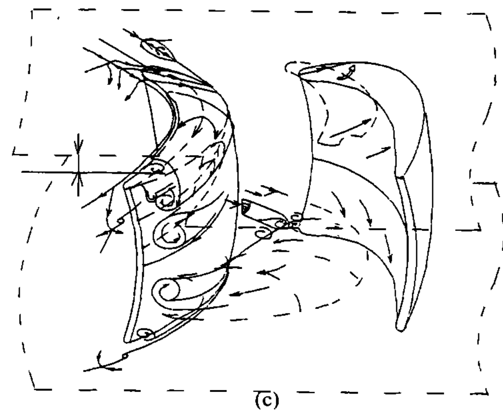


Fig. 9 Vortex structure of cascade with tip clearance($\tau = 0.036$)
(a) conventional straight cascade;
(b) positively curved cascade;
(c) negatively curved cascade;

3.4 The effect of topology and vortex structures on relative leakage and energy loss

According to the experimental result, the topology and vortex structures of the cascade affect the leakage and energy loss greatly. In the same one set of cascades, most singular points, separation lines and vortexes lie on the upper side of the cascade. From the energy loss coefficient along the blade height in Fig. 10, it can be seen that a higher energy loss coefficient occurs on the upper side of the cascade. Under the same tip clearance, the positively curved cascade has the minimum numbers of singular points, separation lines and vortices and the least total energy loss (Figs. 8, 11). By Comparison of the same kind of cascade with different clearances, it is obvious that the numbers of singular points, separation lines and vortices increase, and energy loss goes higher with the increase of clearance (Figs. 8, 11). In addition, in cascades with the same topology and vortex structures, both the positions in which singular points and separation lines are created and the vortex intensity have their effects on the flow loss. The straight cascade and negatively curved cascade have the same topology and vortex structures except the different distribution of singular points, and thus the flow loss of the negatively curved cascade is larger than that of the straight cascade.

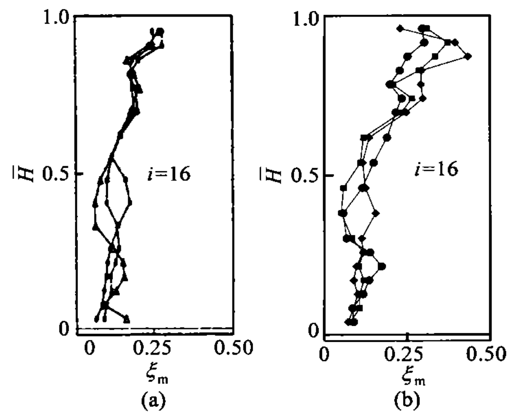


Fig. 10 Distribution of pitch averaged energy loss coefficient along blade height at outlet of cascade. (a) τ= 0.023; (b) τ= 0.036

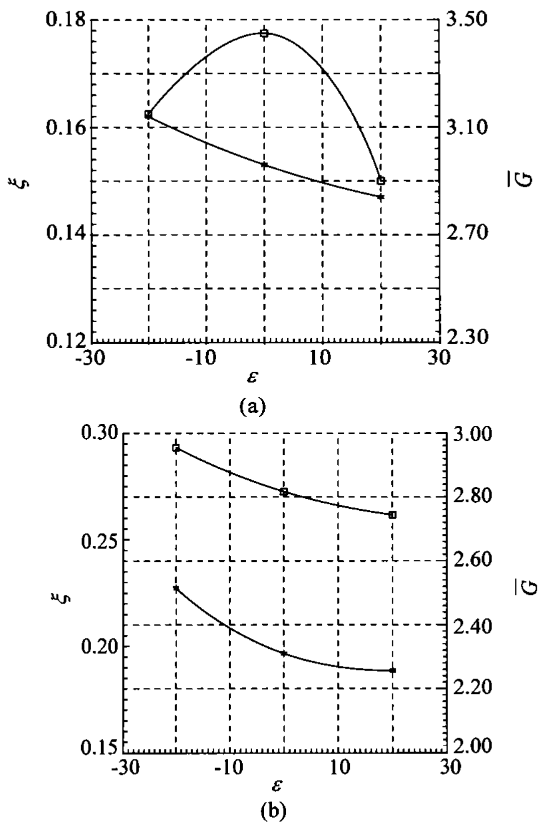


Fig. 11 Relation of relative leakage and energy loss coefficient with blade type
(a) τ= 0.023; (b) τ= 0.036
* – energy loss □ – relative leakage mass flow

The key factors that affect the relative leakage are tip clearance, pressure difference between the suction and pressure surfaces and flow separation of the blade tip. Under the same clearance, the pressure difference has an effect opposite to that of the separation on the relative leakage. Fig. 11 (a) shows that the blade tip pressure difference and separation of the straight cascade are the smallest, the same as leakage. The pressure difference of the negatively curved cascade is the largest, but its leakage is smaller than that of the straight cascade, which is due to the severe separation in the blade tip of the negatively curved cascade. From the fact, it can be said that under small clearance, the resistant effect of the blade tip separation caused by the blade negative curving on the leakage is larger than that of the forcing effect of the increment of pressure difference. Fig. 11 (b) shows that for the same reason, the positively curved cascade has the least leakage and the negatively curved cascade the largest. The latter shows that under large clearance, the driving effect of the blade tip pressure difference caused by the blade negative curving on the leakage is larger than the resistant effect of the worse blade tip separation. Comparing the relative leakage of the same kind of cascade with different clearances, as in Fig. 11, shows that the leakage reduces with the increasing of clearance, which may be due to the result of the more uniform blade tip pressure and the worse blade tip separation with the increasing of clearance. To work on the complex effect of blade tip clearance, more experimental data will be needed.

4 Conclusions

In a turbine cascade with tip clearance, due to the effect of leakage flow, most singular points, separation lines and centralized vortices lie in the upper half span, especially in its suction surface wall corner, and the leakage vortex interacts with the upper passage vortex, generating a great energy loss. This effect becomes stronger with the increasing of relative clearance.

Under different clearances of τ= 0.023 and τ

= 0.036, the blade positive curving is able to eliminate the upper passage vortex, waken the blade tip separation, decrease the pressure difference between the blade tip suction and pressure surfaces, and thus reduces the relative leakage and energy loss.

Under small clearance, the driving effect of the increment of blade tip pressure difference caused by the blade negative curving on the leakage is less than the resistant effect of the worse blade tip separation. While under large clearance, the driving effect of the increment of blade tip pressure difference caused by the blade negative curving on the leakage is greater than the resistant effect of the worse blade tip.

Under different clearances, the blade negative curving, instead of changing the topology and vortex structures of the cascade wall surface flow, only causes forwards the positions in which vortexes are generated, increases the vortex intensity, scale and its partnering effect, and thus leads to the increasing of energy loss in flow.

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Biographies:

HAN Wan-jin Born in 1942, he is a professor and a doctoral supervisor in Harbin Institute of Technology. His main research interests include cascade aerodynamic study and experimental investigation. He has published more than 60 scientific papers. Tel: (0451) 6413243.

HUANG Hong-yan Born in 1968, as an associate professor, he is working in Academy of Energy Science and Engineering, Harbin Institute of Technology. His main research interests include numerical simulation and experimental study of flow fields in cascades. He has published more than 20 scientific papers. Tel: (0451) 6413243, 6412646. E-mail: newhhy2001@263.net, or dyjhhy2001@yahoo.com.

Erratum:

Foundation items of the paper

Investigation on Oxidation Behavior of Al-Cu-Fe Quasi-crystal

ZHOU Chun-gen, XU Hui-bin, GONG Sheng-kai, KANG Guang-ming

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